

## SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

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Viborg, Denmark, a Danish citizen, have invented certain new and use-

5 ful improvements in a METHOD FOR DETERMINING FAULTS DURING THE

OPERATION OF A PUMP UNIT of which the following is a specification:

## FIELD OF THE INVENTION

The invention relates to a method for determining faults on operation of a pump assembly, in particular of a centrifugal pump assembly, according to the features specified in the introductory part of claim 1, as well as a suitable device for carrying out this method, according to claim 18.

## BACKGROUND OF THE INVENTION

10 In the meanwhile, it is counted as belonging to the state of the art to provide a multitude of sensor systems with pump assemblies, on the one hand to detect operating conditions, and on the other hand to also determine faulty conditions of the installation and/or of the pump assembly. With this, it is disadvantageous that the sensor system required with regard to this, is not only complicated and expensive, but is often also susceptible to faults.

20 Against this background, it is the object of the invention, to provide a method for determining faults on operation of a pump assembly which may be carried out with as little as possible sensor technology, as well as a device for carrying out the method.

## SUMMARY OF THE INVENTION

25 According to the invention, this object is achieved by the features specified in claim 1 and 2. A corresponding device is defined by

the features of claim 18. Advantageous formations of the method according to the invention as well as of the device according to the invention are to be deduced from the dependent claims, the subsequent description and the figures.

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#### DETAILED DESCRIPTION OF THE INVENTION

The basic concept of the invention is to acquire data characteristics of the electrical motor as well as the hydraulic-mechanical pump by way of electrical variables of the motor, which as a rule are available anyway or at least may be determined with little effort, as well as by way of at least one changing hydraulic variable of the pump which as a rule is to be determined by sensor, and to evaluate this characteristic data, as the case may be, after mathematical operations (linking). In the simplest form, this is effected by way of comparison to predefined values, wherein the comparison as well as the result is effected automatically by way of electronic data processing, which thus ascertains whether a fault is present or not on operation of the pump.

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The method according to the invention, for determining faults on operation of a pump assembly, thus envisages at least two variables determining the electrical power of the motor, and at least one changing hydraulic variable of the pump being detected, and these detected values or values derived therefrom being compared to predefined values, and determining whether a fault is present or not. This is all effected automatically by way of electronic data processing. The method according to the invention requires a minimum of sensor technology and as a rule may be implemented with regard to software with modern pumps which are typically controlled by frequency converter and have a digital data processing in any case. Thereby, it is particularly advantageous that the variables determining the electrical power

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of the motor, specifically typically the voltage prevailing at the motor, and the current feeding the motor, are available in any case within the frequency converter electronics, so that for determining a hydraulic variable, e. g. the pressure, only a pressure sensor is required, which  
 5 moreover is already often counted as belonging to standard equipment with modern pumps. The predefined values required for the comparison may be stored in digital form in suitable memory components of the motor electronics.

10 Alternatively to the comparison with characteristic values of the motor and pump stored in a tabular form, according to claim 2, it is envisaged on the one hand for the two electrical variables of the motor determining the electronic power of the motor, preferably the voltage prevailing at the motor and the current feeding the motor, to be  
 15 mathematically linked for achieving at least one comparison value, and on the other hand for the at least one changing hydraulic variable of the pump as well as a further mechanical or hydraulic variable determining the power of the pump to be mathematically linked for achieving at least one further comparison value, wherein then one de-  
 20 termines whether a fault is present or not by way of the result of the mathematical linking by way of comparison with predefined values. The mathematical linking thereby is effected for the data on the part of the motor by way of suitable equations determining the electrical and/or magnetic relations in the pump, whereas equations which de-  
 25 scribe the hydraulic and/or mechanical system are used for the pump. The values resulting with the respective linking are compared either directly or to predefined values stored in the memory electronics, whereupon the electrical data processing automatically ascertains whether an error is present or not. With the direct comparison, the error variable  
 30 is determined as a variation between a variable resulting from the motor model e.g.  $T_e$  or  $\omega$  and a corresponding variable resulting from the mechanical-hydraulic model. The method according to claim 2 in con-

trast to that according to claim 1, has the advantage that less memory space is required for the predefined values, but however this method requires more computation capability of the computer.

5           Thereby, with the method according to the invention, one may not only ascertain whether a fault is present, but moreover one may also yet specify the faults, i. e. determine as to which faults are present.

Advantageously, the pressure or differential pressure produced  
10       by the pump is used as a hydraulic variable to be detected, since this variable may be detected on the part of the assembly, and the provision of such a pressure recorder is nowadays counted as belonging to the state of the art with numerous pump construction types.

15           Alternatively or additionally to detecting the pressure, it may also be advantageous to use the quantity delivered by the pump as a hydraulic variable. The detection of the delivery quantity may likewise be effected on part of the assembly, and here too, less complicated measurement systems which are stable over the longer term are avail-  
20       able.

Since the absolute pressure detection of the pressure produced by the pump always represents a differential pressure measurement with respect to the outer atmosphere, it is often more favorable to de-  
25       tect the differential pressure formed between the suction side and the pressure side of the pump, instead of the absolute pressure, which furthermore as a hydraulic variable of the pump is processed in a significantly more favorable manner.

30           Advantageously, one uses a mechanical-hydraulic pump/motor model for the mathematical linking for the variables determining the electrical power of the motor and for the mathematical linking of the

mechanical-hydraulic pump variable. Thereby, as an electrical motor model, it is preferred to use one defined by the equations (1) to (5) or (6) to (9) or (10) to (14).

$$L'_s \frac{di_{sd}}{dt} = -R'_s i_{sd} + \frac{L_m}{L_r} (R'_r \psi_{rd} + z_p \omega \psi_{rq}) + v_{sd} \quad (1)$$

$$L'_s \frac{di_{sq}}{dt} = -R'_s i_{sq} + \frac{L_m}{L_r} (R'_r \psi_{rq} - z_p \omega \psi_{rd}) + v_{sq} \quad (2)$$

$$\frac{d\psi_{rd}}{dt} = -R'_r \psi_{rd} - z_p \omega \psi_{rq} + R'_r L_m i_{sd} \quad (3)$$

$$\frac{d\psi_{rq}}{dt} = -R'_r \psi_{rq} + z_p \omega \psi_{rd} + R'_r L_m i_{sq} \quad (4)$$

$$T_e = z_p \frac{3}{2} \frac{L_m}{L_r} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) \quad (5)$$

- 5 The equations (1) to (5) represent an electrical, dynamic motor model for an asynchronous motor.

$$V_s = Z_s(s) I_s \quad (6)$$

$$\omega = \omega_s - s \omega_s \quad (7)$$

$$I_r = \frac{V_s}{Z_r(s)} \quad (8)$$

$$T_e = \frac{3 R_r I_r^2}{s} \quad (9)$$

- 10 The equations (6) to (9) represent an electrical, static motor model likewise for an asynchronous motor.

$$L_s \frac{di_{sd}}{dt} = -R_s i_{sd} + z_p \omega L_s \psi_{rq} + v_{sd} \quad (10)$$

$$L_s \frac{di_{sq}}{dt} = -R_s i_{sq} - z_p \omega L_s \psi_{rd} + v_{sq} \quad (11)$$

$$\frac{d\psi_{rd}}{dt} = -z_p \omega \psi_{rq} \quad (12)$$

$$\frac{d\psi_{rq}}{dt} = z_p \omega \psi_{rd} \quad (13)$$

$$T_e = z_p \frac{3}{2} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) \quad (14)$$

The equations (10) to (14) represent an electrical dynamic motor model, and specifically for a permanent magnet motor.

In the equations (1) to (14) are represented:

$i_{sd}$	the motor current in direction d
$i_{sq}$	the motor current in direction q
$\psi_{rd}$	the magnetic flux of the rotor in the d-direction
$\psi_{rq}$	the magnetic flux of the rotor in the q-direction
$T_e$	the motor moment
$v_{sd}$	the supply voltage of the motor in the d-direction
$v_{sq}$	the supply voltage of the motor in the q-direction
$\omega$	the angular speed of the rotor and impeller
$R'_s$	the equivalent resistance of the stator winding
$R'_r$	the equivalent resistance of the rotor winding
$L_m$	the inductive coupling resistance between the stator- and the rotor winding
$L'_s$	the inductive equivalent resistance of the stator winding
$L_r$	the inductive resistance of the rotor winding
$z_p$	the polar pair number
$I_s$	the phase current
$V_s$	the phase voltage
$\omega_s$	the frequency of the supply voltage
$\omega$	the actual rotor- and impeller rotational speed
$s$	the motor slip
$Z_s(s)$	the stator impedance
$Z_r(s)$	the rotor impedance
$R_r$	the equivalent resistance of the rotor winding
$R_s$	the equivalent resistance of the stator winding
$L_s$	the inductive resistance of the stator winding

wherein d and q are two directions perpendicular to the motor shaft and perpendicular to one another.

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The equation (15) and at least one of the equations (16) and (17) are advantageously applied for the mechanical-hydraulic pump/motor model.

Thereby, the equation (15) represents the mechanical relationships between the motor and the pump, whereas the equations (16) and (17) describe the mechanical-hydraulic relationships in the pump. These equations are:

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$$J \frac{d\omega}{dt} = T_e - B\omega - T_p \quad (15)$$

and at least one of the equations

$$H_p = -a_{h2}Q^2 + a_{h1}Q\omega + a_{h0}\omega^2 \quad (16)$$

$$T_p = -a_{t2}Q^2 + a_{t1}Q\omega + a_{t0}\omega^2 \quad (17)$$

in which

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$\frac{d\omega}{dt}$	describes the temporal derivative of the angular speed of the rotor,
$T_p$	the pump torque,
$J$	the moment of inertia of the rotor, impeller and the delivery fluid contained in the impeller,
$B$	the friction constant,
$Q$	the delivery flow of the pump,
$H_p$	the differential pressure produced by the pump,
$a_{h2}, a_{h1},$ $a_{h0}$	the parameters which describe the relationship between the rotational speed of the impeller, the delivery flow and the differential pressure and
$a_{t2}, a_{t1},$ $a_{t0}$	the parameters which describe the relation between the rotational speed of the impeller, the delivery flow and the moment of inertia

By way of example, claim 9 defines in which manner the mathematical linking is carried out, in order to determine whether faults are present or not. In principle, one may here completely make do without storing predefined values. The basic concept of this specific method lies one the one hand, with the aid of the motor model, in determining the motor moment resulting on account of the electrical variables at the



variables at the motor shaft, as well as the rotational speed, wherein the latter may also be measured. A relation between the pressure and delivery quantity on the one hand or between the power/moment and the delivery quantity on the other hand is determined with the help of the equations (16) and/or (17). Then, advantageously with equation (15), one checks as to whether the variables computed with the help of the motor model agree or not to those variables computed with the help of the pump model after substitution with the measured hydraulic variable, wherein a fault is registered should they not agree. One therefore quasi compares, whether the drive variables resulting from the electrical motor model agree or not with those drive variables resulting from the hydraulic-mechanical pump model. If this is the case, the pump assembly functions without faults, otherwise a fault is present which as the case may be, may be yet specified further.

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In order to provide the system with a certain amount of tolerance, it may be useful, by way of variance of at least one of the variables  $a_{10}$  to  $a_{12}$ ,  $B$  and  $J$ , to define a tolerance range, in order then to only register a fault when this is also relevant to operation.

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In order to be able to specify the type of fault in a more accurate manner, it is useful additionally to the two electrical variables, to determine two hydraulic variables, preferably by way of measurement, and to substitute the determined variables into the equations according to claim 8, so that four error variables  $r_1$  to  $r_4$  then result. The type of fault is then determined by way of predefined boundary value combinations. This too is effected automatically by way of the electronic data processing.

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In an alternative further formation of the method according to the invention, for determining the type of fault, additionally to the two electrical variables, one may also determine two hydraulic variables,

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- preferably by measurement, and compare the determined values to predefined values, wherein then in each case, the predefined values define a surface in three-dimensional space, and one determines as to whether the determined variables lie on these surfaces ( $r^*_1$  to  $r^*_4$ ) or not,
- 5 and on account of the combination of the values, one determines the type of fault by way of predefined boundary value combinations. The fault type may for example be determined for example by way of the following table:

fault type	fault variable	$r_1$	$r_2$	$r_3$	$r_4$
	comparative surface	$r_1^*$	$r_2^*$	$r_3^*$	$r_4^*$
increased friction on account of mechanical defects		1	0	1	1
reduced delivery/absent pressure		0	1	1	1
defect in suction region/absent delivery quantity		1	1	0	1
delivery stoppage		1	1	1	1

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- It is therefore possible with the help of the method according to the invention to not only ascertain or not the fault-free operating condition of the pump assembly but also in the case of a fault, to specify this in detail with a minimum of sensor technology, so that a corresponding
- 15 fault signal may be generated in the pump assembly, which displays the type of fault. This signal, as the case may be, may be transferred to distanced locations, where the function of the pump assembly is to be monitored.

- 20 The surfaces in the three-dimensional space which are formed by way of predefined values are typically spatially arcuate surfaces,

whose values are previously determined at the factory on account of the respective assembly or assembly type, and on the part of the assembly are stored in the digital data memory. Thereby, the previously mentioned comparative surfaces  $r^*_1$  to  $r^*_4$  are arranged in a three-dimensional space, which at  $r^*_1$  are formed from the torque, the throughput and the rotor speed, at  $r^*_2$  from the delivery head, the delivery quantity and the rotor speed, for  $r^*_3$  from the torque, the delivery head and the rotor speed, as well as for  $r^*_4$  from the torque, the delivery head and the delivery quantity.

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The variables defined in the table by the comparative surfaces  $r^*_1$  to  $r^*_4$  characterise the respective operating condition, wherein the numeral 0 indicates that the respective value lies within the surface defined by the predefined values, and 1 that it lies outside this. Thus the fault combination defined in the table due to increased friction on account of mechanical defects may for example indicate bearing damage, or an increased friction resistance between the rotating parts and the stationary parts of the assembly, caused in any other manner. The fault combination characterised under the main term of reduced delivery/absent pressure may for example be caused by fault or wear of the pump impeller, or an obstacle in the pump inlet or outlet. The fault combination defined under the main term of defect in the suction region/absent delivery quantity may for example be caused by a defect of the ring seal at the suction port of the pump. The fault combination falling under the main term of delivery stoppage may have the most varied of causes and, as the case may be, is to be specified further. This delivery stoppage may be caused by a blocked shaft or a blocked pump impeller, by way of a failure of the shaft, by way of a detachment of the pump impeller, by way of cavitation on account of an unallowably low pressure at the pump inlet, as well as by way of running dry.

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The operating conditions characterised in the table by way of the variables  $r_1$  to  $r_4$  are based on mathematical computations of fault variables  $r_1$  to  $r_4$  according to the equations (19) to (22), wherein the respective fault variable assumes the value zero when a perfect operation is present, and the value 1 in the case of a fault. The table with regard to the fault type is to be understood in a manner corresponding to that described above. Pictured, each of the fault variables  $r_1$  to  $r_4$  represents a distance to the respective surfaces  $r^*_1$  to  $r^*_4$ . However, the fault variables do not necessarily need to correspond with the surfaces  $r^*_1$  to  $r^*_4$ . The fault variables  $r_1$  to  $r_4$  correspond to the equations (19) to (22) and correspond to the surfaces  $r^*_1$  to  $r^*_4$  in the Figures 7 to 10.

In order to further differentiate the type of fault, in a further embodiment of the invention, it is envisaged to activate the pump assembly with a changed rotational speed on determining the fault, in order to then be able to pinpoint the determined fault in a closer manner on account of the measurement results which then set in.

Preferably the mechanical-hydraulic pump/motor model not only includes the pump assembly itself, but also at least parts of the hydraulic system which is affected by the pump, so that faults of this hydraulic system may also be determined.

Thereby, the hydraulic system is advantageously defined by the equation (18) which represents the change of the delivery flow over time.

$$K_J \frac{dQ}{dt} = H_p - (p_{out} + \rho g z_{out} - p_m - \rho g z_m) - (K_v + K_l) Q^2 \quad (18)$$

in which

- $K_J$  is the constant which describes the mass inertia of the fluid column in the pipe system,
- $K_v$  the constant which describes the flow-dependent pressure

- losses in the valve, and  
 $K_L$  is the constant which describes the flow-dependent pressure losses in the pipe system,  
 $H_p$  the differential pressure of the pump,  
 $P_{out}$  the pressure at the consumer-side end of the installation,  
 $P_{in}$  the supply pressure,  
 $Z_{out}$  the static pressure level at the consumer-side end of the installation,  
 $Z_{in}$  the static pressure level at the pump entry,  
 $\rho$  the density of the delivery medium,  
 $g$  the gravitational constant

are,

The fault variables  $r_1$  to  $r_4$  are advantageously defined by the equations

5 (19) to (22):

$$\begin{cases} J \frac{d\hat{\omega}_1}{dt} = -B\hat{\omega}_1 - (-a_{12}Q^2 + a_{11}Q\omega + a_{10}\omega^2) + T_e + k_e(\omega - \hat{\omega}_1) \\ r_1 = q_1(\omega - \hat{\omega}_1) \end{cases} \quad (19)$$

$$\begin{cases} r_2 = q_2(-a_{12}Q^2 + a_{11}Q\omega + a_{10}\omega^2 - H_p) \end{cases} \quad (20)$$

$$\begin{cases} Q' = \frac{a_{11}\omega + \sqrt{a_{11}^2\omega^2 - 4a_{12}(H_p + a_{10}\omega^2)}}{2a_{12}} \\ J \frac{d\hat{\omega}_3}{dt} = -B\hat{\omega}_3 - (-a_{12}Q'^2 + a_{11}Q'\omega + a_{10}\omega^2) + T_e + k_3(\omega - \hat{\omega}_3) \\ r_3 = q_3(\omega - \hat{\omega}_3) \end{cases} \quad (21)$$

$$\begin{cases} \omega' = \frac{-a_{11}H_p + \sqrt{a_{11}^2H_p^2 - 4a_{12}(H_p + a_{10}Q^2)}}{2a_{12}} \\ J \frac{d\hat{\omega}_4}{dt} = -B\hat{\omega}_4 - (-a_{12}Q^2 + a_{11}Q\omega' + a_{10}\omega'^2) + T_e + k_4(\omega' - \hat{\omega}_4) \\ r_4 = q_4(\omega' - \hat{\omega}_4) \end{cases} \quad (22)$$

in which

- 
- $k_1, k_3, k_4$  are constants,  
 $q_1, q_2, q_3, q_4$  constants,  
 $Q'$  the computed delivery quantity on the basis of current rotational speed and measured pressure,  
 $\hat{\omega}_1$  the computed rotor rotational speed on the basis of the mechanical-hydraulic equations (15) and (17),  
 $\hat{\omega}_3$  the computed rotor rotational speed on the basis of equations (15), (16) and (17),  
 $\hat{\omega}_4$  the computed rotor rotational speed on the basis of equations (15), (16) and (17),

- $\omega'$  the computed rotor rotational speed on the basis of the measured delivery pressure and measured delivery quantity
- $r_1 - r_4$  fault variables, and
- $r_1^* - r_4^*$  surfaces determined by three variables, which represent a fault-free operation of the pump.

- In order to carry out the inventive method for determining faults with operational conditions of a centrifugal pump assembly, there,
- 5 means are provided for detecting two electrical variables determining the power of the motor, as well as means for detecting at least one changing hydraulic variable of the pump, as well as an electronic evaluation means which determines a fault condition of the pump assembly on account of the detected variables. In its simplest form, here
- 10 sensor means for detecting the supply voltage present at the motor and the supply current as well as for detecting the pressure, preferably differential pressure produced by the pump, and the delivery quantity or the rotational speed are to be provided. Furthermore, an evaluation means is to be provided, which may be designed in the form of a digital data processing, e.g. a microprocessor, in which the method according to the invention may be implemented with regard to software. An electronic memory is further to be provided in order to be able carry out the comparison between detected or computed values and pre-defined values (e.g. detected and stored on the part of the factory).
- 20 With modern pump assemblies controlled by frequency converter, all the previous preconditions with regard to hardware are already present, so that one must only ensure an adequate dimensioning of the electronic data processing installation, in particular of the memory means and the evaluation means. All components with the exception
- 25 of the sensor system required for the detection of the hydraulic variables are preferably an integral component of the motor electronics and/or pump electronics, so that inasmuch as concerned, construc-

tively no further provisions are to be made for implementing the method according to the invention. Another embodiment form may be a separate component to be provided in a switch panel or control panel, in the same manner as a motor circuit breaker, but with the monitoring and diagnosis properties as described above.

The embodiment forms described here relate to centrifugal pumps, as this also results from the mechanical-hydraulic pump model. Such pumps may for example be industrial pumps, submersible pumps for the sewage or for the water supply, as well as heating circulation pumps. A diagnosis system according to the invention is particularly advantageous with canned motor pumps, since as a precaution, one may prevent the grinding-through of the can and thus the exit of delivery fluid, e.g. into the living rooms by way of the early fault recognition. On application of the invention in the field of displacement pumps, the mechanical-hydraulic pump model must be adapted according to the differing physical relationships. The same also applies to the electrical motor model with the application of other motor types.

Furthermore, according to the invention, means are provided in order to produce at least one fault notification and to transit it to a display element which is arranged on the pump assembly or somewhere else, be it in the form of one or more control lights, or of a display with an alpha-numeric display. Thereby, the transmission may be effected in wireless manner, for example via infrared or radio, or also be connected by wire, preferably in a digital form.

The method according to the invention is shown in its simplified form by way of Fig. 1. The changing electrical variables determining the power, here, in particular the voltage  $V_{abc}$  and the current  $i_{abc}$  flow into an electrical motor model. The product of these variables defines the electrical power taken up by the motor. The torque  $T_m$  at the shaft of

the motor as well as the rotational speed  $\omega$  of the motor, as result numerically on account of the motor model, may be deduced from this motor model as is given for example by the equations (1) to (5) or (6) to (9) or (10) to (14). These electrical variables of the motor which are dependent on the power are linked with the determined mechanical delivery head  $H$  (pressure) in a pump model 2, for example according to the equations (16) and (17), wherein then the result is compared with operational values which are determined and predefined by way of defined operating points. The pump assembly operates without faults on agreement of these input variables with the predefined values. If however a difference beyond a certain measure results, then an error signal  $r$  is generated, which signalizes a faulty function of the pump.

With the embodiment according to Fig. 2, in the same manner as with Fig. 1, the input voltage  $v_{abc}$  and the motor current  $i_{abc}$  are used as input values for the motor model 1, in order to determine the torque  $T_e$  prevailing at the motor shaft and the rotational speed of the shaft  $\omega$ . These values derived from the motor model 1, as well as the variables of the delivery head  $H$  (pressure) as well as delivery quantity  $Q$  determined by sensor are mathematically linked to one another in a mechanical-hydraulic pump model 3, which e.g. is formed further by the equations (19) to (22). Here, four error variables  $r_1$  to  $r_4$  are generated, wherein a fault-free operation is present when these all assume the value zero and thus the operating points lie in the surfaces  $r^*_1$  to  $r^*_4$  represented individually in the Figures 7 to 10. These surfaces represented there are defined by a multitude of operating points on envisaged proper operation of the pump assembly, and are produced on the part of the factory and are digitally stored in memory component of the evaluation electronics. Alternatively or additionally, it is ascertained whether the error variables  $r_1$  to  $r_4$  determined on account of the mechanical-hydraulic pump model are zero or not, and an evaluation according to the previously described table is effected according to



this result. Depending on whether an error variable is present or not on occurrence of a fault, as a whole four erroneous operating conditions of the pump assembly may be ascertained, and specifically, those falling under the previously mentioned terms:

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1. increased friction on account of a mechanical defect,
2. reduced delivery/absent pressure,
3. defect in the suction region/absent delivery quantity,
- and
4. delivery stoppage.

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With the method according to the invention, one may not only monitor the pump assembly itself, but also parts of the installation in which the pump assembly is arranged may be monitored. Thereby, the system is broken down as is shown in detail in Fig. 3. Here too, an electrical motor model is provided, whose input variables are  $V_{abc}$  and  $i_{abc}$ , and on which a static motor model according to the equations (6) to (9) is based, such as has been known until now and is represented by way of Fig. 5. The output variable of this static motor model is the motor moment  $T_e$ , which in turn flows into the mechanical part of the pump model 3a via the equation (15). The hydraulic part of the pump model 3b is defined by the equations (16) and (17), via which the hydraulic part of the installation 4 is coupled. The hydraulic part of the installation is defined by the equation (18) and is schematically represented by way of Fig. 4, in which  $P_{in}$  represents the pressure supply of the pump,  $H_p$  the differential pressure of the pump,  $Q$  the delivery flow,  $P_{out}$  the pressure at the consumer-side end of the installation and  $V_l$  the flow losses within the pump.  $Z_{out}$  is the static pressure level at the consumer-side end of the installation and  $Z_{in}$  that at the pump entry.

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Fig. 3 thus emphasizes the relationships between the motor model, the mechanical part of the pump model, the hydraulic part of

the pump model and the hydraulic part of the installation. Whereas the delivery head and the delivery quantity enter and exit in and out of the hydraulic parts of the pump model 3b and the hydraulic part of the installation, the rotational speed  $\omega_r$  which also enters into the motor model, enters into the hydraulic part of the pump model 3b. The moment evaluated from the hydraulic part of the pump model 3b in turn enters into the mechanical part of the pump model 3a for determining the rotational speed.

The previously described equations for the mathematical description of the pump and motor are only to be understood by way of example and may, as the case may be, be replaced by other suitable equations as are known from the relevant technical literature. The above faults which may be determined with these models on operation of a pump assembly, or the differentiation according to fault types may be further diversified by way of suitable fault algorithms.

In order to ensure that already small manufacturing tolerances or measurement errors do not lead to the issuing of fault signals, it is useful not to select the parameters  $a_h$  and  $a_i$  specified in the equations (16) and (17) in a constant manner, but in each case to fix a lower or upper boundary value in order to produce a certain bandwidth, as is shown in Fig. 6. In the left curve shown there, the power is plotted against the delivery quantity, and in the right curve, the delivery head is plotted against the delivery quantity.

**List of reference numerals**

- 1 - electrical motor model
- 2 - simplified pump model
- 5 3 - extended pump model
- 3a - mechanical part of the pump model
- 3b - hydraulic part of the pump model
- 4 - hydraulic part of the installation